



Developing recommendations for increased productivity in cassava-maize intercropping systems in Southern Nigeria

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ARTICLE INFO

Keywords:

Cassava maize intercropping
Plant density
Fertilizer
Value cost ratio
Profitability
Southern Nigeria

ABSTRACT

Cassava-maize intercropping is a common practice among smallholder farmers in Southern Nigeria. It provides food security and early access to income from the maize component. However, yields of both crops are commonly low in farmers' fields. Multi-locational trials were conducted in Southern Nigeria in 2016 and 2017 to investigate options to increase productivity and profitability through increased cassava and maize plant densities and fertilizer application. Trials with 4 and 6 treatments in 2016 and 2017, respectively were established on 126 farmers' fields over two seasons with a set of different designs, including combinations of two levels of crop density and three levels of fertilizer rates. The maize crop was tested at low density (LM) with 20,000 plants ha⁻¹ versus high density (HM) with 40,000 plants ha⁻¹. For cassava, low density (LC) had had 10,000 plants ha⁻¹ versus the high density (HC) with 12,500 plants ha⁻¹. The fertilizer application followed a regime favouring either the maize crop (FM: 90 kg N, 20 kg P and 37 kg K ha⁻¹) or the cassava crop (FC: 75 kg N, 20 kg P and 90 kg K ha⁻¹), next to control without fertilizer application (F0). Higher maize density (HM) increased marketable maize cob yield by 14 % (3700 cobs ha⁻¹) in the first cycle and by 8% (2100 cobs ha⁻¹) in the second cycle, relative to the LM treatment. Across both cropping cycles, fertilizer application increased cob yield by 15 % (5000 cobs ha⁻¹) and 19 % (6700 cobs ha⁻¹) in the FC and FM regime, respectively. Cassava storage root yield increased by 16 % (4 Mg ha⁻¹) due to increased cassava plant density, and by 14 % (4 Mg ha⁻¹) due to fertilizer application (i.e., with both fertilizer regimes) but only in the first cropping cycle. In the second cycle, increased maize plant density (HM) reduced cassava storage root yield by 7% (1.5 Mg ha⁻¹) relative to the LM treatment. However, the negative effect of high maize density on storage root yield was counteracted by fertilizer application. Fresh storage root yield increased by 8% (2 Mg ha⁻¹) in both fertilizer regimes compared to the control without fertilizer application. Responses to fertilizer by cassava and maize varied between fields. Positive responses tended to decline with increasing yields in the control treatment. The average value-to-cost ratio (VCR) of fertilizer use for the FM regime was 3.6 and higher than for the FC regime (VCR = 1.6), resulting from higher maize yields when FM than when FC was applied. Revenue generated by maize constituted 84–91% of the total revenue of the cropping system. The highest profits were achieved with the FM regime when both cassava and maize were grown at high density. However, fertilizer application was not always advisable as 34 % of farmers did not realize a profit. For higher yields and profitability, fertilizer recommendations should be targeted to responsive fields based on soil fertility knowledge.

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<https://doi.org/10.1016/j.fcr.2021.108283>

Received 10 April 2021; Received in revised form 16 August 2021; Accepted 27 August 2021

Available online 31 August 2021

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1. Introduction

In Africa, the finite natural reserves of nutrients in soils are declining at a fast rate because smallholder farmers generally do not implement measures to replenish nutrient stocks. This leads to a continuous decrease in crop productivity (Yadav et al., 2017). Agricultural land use in Africa has been intensified in response to an increasing food demand driven by population pressure (Sommer et al., 2013) but with a minimal increase in input use. This has resulted in nutrient depletion and soil degradation of agricultural lands due to continued nutrient mining (Thierfelder, 2013). Today, it is no longer possible to rely on long fallow phases to restore soil fertility. Hence, the natural accumulation of nutrients and soil organic matter (SOM) to support crop production is no more attainable, and thus, external nutrient inputs are required to sustain crop production (Sommer et al., 2013).

Intercropping is an agricultural intensification strategy proposed to increase food production while addressing some environmental issues (Midmore, 1993). Intercropping systems produce as much as 15–20% of the world's food supply and can increase food security while reducing risk (Javaid et al., 2015). According to Delaquis et al. (2018), some of the remarkable benefits of cassava-based intercropping systems include pest and disease suppression, land-use efficiency, and soil- and water-regulating services. Cassava-maize intercropping is reported to be the most popular crop mixture in tropical regions, including Nigeria (Ayoola and Makinde, 2007). Cassava is a suitable intercrop for maize due to its initial slow growth, wide spacing, and longer growing period (8–15 months) before it is harvested (Silva et al., 2016). Peak nutrient demand of the two crops also occur at different times and their root systems reach different depths, thus should be able to utilize available nutrients from varying soil depths (Adiele et al., 2020; Duchene et al., 2017). Furthermore, maize provides food and income early in the season (at 3–4 months after planting), well before the cassava harvest (8–15 months later). From an ecological perspective, intercropping cassava with other short-season crops like maize was reported to reduce the risk of soil erosion, weed density, nutrients loss, and improve soil moisture content (Ekeleme et al., 2003; Olasantan et al., 1996).

As an affordable and energy-rich staple, cassava is an important constituent of sub-Saharan Africa (SSA) diets, particularly in western and central Africa where per capita consumption exceeds that of any cereal product. Maize accounts for 30–50% of low-income household expenditure in Africa (IITA, 2021). Over 30 % of the caloric intake of people in Sub-Saharan Africa comes from maize (IITA, 2021; Makurira, 2010). Yet, currently, both crops produce low yields in SSA. Average yields are about 9–12 t ha⁻¹ for cassava (Adiele et al., 2020; Fermont et al., 2009) and less than 1 t ha⁻¹ for maize (Sommer et al., 2013) in farmers' fields, while attainable yields are over 40 t ha⁻¹ for cassava (Ezui et al., 2017; Fermont et al., 2007) and between 5–7.5 t ha⁻¹ for maize (Meng et al., 2013; Rusinamhodzi et al., 2012). This indicates a substantial yield gap and reflects the challenge farmers face in subsistence agriculture (Fermont, 2010; Ntawuruhunga et al., 2006).

Poor crop management, especially inadequate weed control, sub-optimal planting density, and inadequate nutrient management, generally reduce crop productivity (Kintché et al., 2017), and is usually aggravated in intercropping situations due to interspecific competition between companion species (Andersen, 2005; Li et al., 2001). In addition to other poorly executed agronomic operations in farmers' fields, the low productivity of cassava-maize intercropping systems in southern Nigeria can be attributed to poor nutrient supply practices and sub-optimal plant population densities. Hence, there is an urgent need to investigate the potential of plant density and fertilizer application in reducing the staggering yield gap of cassava and maize in intercropping systems. Cassava yields can be increased by K supply on K-deficient soils (Ezui et al., 2017; Sogbedji et al., 2015). However, the effect of K on cassava performance is dependent on N supply and availability (Ezui et al., 2017). Inorganic fertilizers have been shown to improve the performance of cassava and maize grown as sole crops and when

intercropped in Nigeria (Olasantan et al., 1996, 1994; Salau et al., 2011). However, there is a need for further investigation on this, especially on a larger scale across different agro-ecologies. Furthermore, there is evidence for the beneficial effects of higher plant population density on yields in both sole and intercropping systems (Howeler and Cadavid, 1990; Njoku and Muoneke, 2008). Nevertheless, planting density above optimum would increase competition and decrease crop yield (Rahmani, 2016). Current farmers' practice consists of planting cassava at 10,000 and maize at 20,000 plants ha⁻¹. Recommendations of 10,000 plants ha⁻¹ in cassava systems (Eke-okoro and Njoku, 2012; Njoku and Muoneke, 2008) are today considered below the optimum (Onasanya et al., 2020) and require further investigation to provide viable recommendations to farmers on the optimum plant density. Similarly, there is no evidence that the blanket fertilizer recommendations for Nigeria (Chukwu, 2019; Obigbesan and Fayemi, 1976) are sustainable for the cassava-maize intercropping, considering soil and climate heterogeneity of Nigerian agro-ecologies.

Because Nigerian farmers are risk-averse and capital-constrained, they are reluctant to invest in fertilizer for their cassava-maize intercropping systems without a clear indication of the return to the investment. Older fertilizer recommendations (Chukwu, 2019; Eze, 2010; Kolawole, 2013) did not consider environmental variability (i.e., differences in soil fertility and rainfall) across different agro-ecologies and thus, may not be suitable as a blanket recommendation to farmers for adoption. Farmers need simple, easy-to-apply methods guiding their decision-making on the crop density and fertilizer use in their cassava-maize intercropping systems based on trials conducted across the diverse agroecology.

To address these knowledge gaps, we investigated the effects of increasing planting density and NPK fertilizer application on maize and cassava yield and profitability of increasing planting density and NPK fertilizer application in a stepwise intensification approach by: (i) increasing cassava plant density from 10,000 to 12,500 ha⁻¹ and maize plant density from 20,000 to 40,000 ha⁻¹; (ii) fertilizer application in high-density intercropping systems, and (iii) increased N or K application rates to evaluate if cassava or maize can be targeted for yield increases. We hypothesized that: i) increasing both the cassava and maize plant densities in the system will increase yields, ii) application of N, P, K fertilizers will increase yields of both crops at increased planting densities, iii) increasing N application relative to K will benefit maize more than cassava, iv) increasing K application relative to N will benefit cassava more than maize, v) response to fertilizer application is location-specific, and vi) investment in NPK fertilizers in cassava-maize intercropping systems is profitable but may require modification based on the prevailing prices of the crop produce and fertilizer.

2. Materials and methods

2.1. Study area

The trials were conducted in the Derived Savanna (DS) and Humid Forest (HF) agro-ecological zones (AEZs) of Nigeria in Anambra (AN), Benue (BN), Cross River (CR), Ogun (OG), and Oyo (OY) States (Fig. 1) in 2016 and 2017. The study areas were chosen based on the popularity of cassava-maize intercropping of collaborating partners. Within the chosen AEZs, rainfall is bimodal and varies between and within the AEZs (Alahira, 2013; Salako, 2003). Rainfall lasts for 7–8 months with peaks in July and September. Rainfalls span from April through October/early November with 4–5 months dry season starting late November through March. Usually, there is a temporal rainfall cease in August termed the 'August break'. The mean annual rainfall of the chosen Local Government Areas (LGAs) of states within the DS and HF AEZs during the experimental cycles is presented in Fig. 2.

In 2016, planting commenced mid-May and lasted till mid-July. In 2017 planting commenced in mid-June and terminated in early August, in Anambra and Cross Rivers States, respectively. In Benue State,

planting commenced mid-June and terminated in early September in 2016 and 2017. In Ogun and Oyo States, planting in 2016 started in early May and ended in late July while in 2017, planting commenced mid-May and ended mid-July. The cassava of the 2016 and 2017 trials was harvested after 12–15 months in 2017 and 2018, respectively, and is herein termed the first (2016/2017) and second (2017/2018) cycle.

2.2. Site selection, trial installations, and soil conditions

Sites in our areas of interest were grouped according to variations in climate, soil, and vegetation characteristics. The grouping informed the decision for the spread of our trials within states and local government areas (LGAs) of interest. It also enabled collaboration with the already existing network of farmers which was established by the State Agricultural Development Projects (ADPs) and supervised by extension agents (EAs). The specific site locations for the implementation of the trials were selected based on the cropping decision of farmers already working with the ADPs. Farmers who had already decided to grow cassava-maize intercrop were identified and selected with the help of the EAs. To ensure compliance with the protocols and good quality of data, a cluster arrangement of the trials was adopted. A total of 19 clusters (intended to host 190 trials) were used in the 5 States. A cluster constituted an area with a 5 km radius containing 8 trials on average. Although not all the intended trials were established (about 5% less), only 126 trials in the 5 States were harvested. The rest were vandalized, poorly managed, or abandoned due to security issues. In 2016, 64 sites were harvested whereas, in 2017, 62 trials were harvested. Fields of 2016 were different from those used in 2017. In most cases, fields of both years were close to each other. Each cluster was supervised by an EA with assistance from an agronomist. Trial installations, fertilizer applications, and harvesting were done by a team comprising of an agronomist, EA, and participating farmer.

To describe our environments and to show fertility variations within and between States, soil data for 0–30 cm depth were extracted from SoilGrids (<https://soilgrids.org/>) at 250 m spatial resolutions and used for site descriptions. In this data, the soil organic carbon (SOC) was determined by dry combustion at 900 °C, pH measurement was in the water on 1:2.5 soil/water ratio, total nitrogen (N) by wet oxidation, available phosphorus (P) according to the analytical procedure of Mehlich III, the soil exchangeable potassium (Exch. K) determined in

1 M NH_4OAc buffered at pH of 7, and the particle size distributions (sand, silt, and clay contents) by the hydrometer method (<https://soilgrids.org/>).

2.3. Experimental design

In the first cycle, four treatments were assigned to plots in two independent sets of on-farm trials (Table 1): (1) farmer practice (control) at 10,000 cassava plants and 20,000 maize plants ha^{-1} without fertilizer (LC-LM-F0), (2) increased crop density with 12,500 cassava plants and 40,000 maize plants ha^{-1} without fertilizer (HC-HM-F0), (3) increased crop density as in (2) with fertilizer applied at (90 kg N, 20 kg P and 37 kg K ha^{-1}) assumed to favour the maize crop (HC-HM-FM); and (4) increased crop density as in (2) with fertilizer applied at (75 kg N, 20 kg P and 90 kg K ha^{-1}) assumed to favour the cassava crop (HC-HM-FC). The planting pattern of the low cassava density was on a square pattern of 1 m \times 1 m, while the high density was on a rectangular pattern of 1 m \times 0.8 m. Low-density maize was seeded at 1 m \times 0.5 m and the high density at 1 m \times 0.25 m. Treatments were not replicated at individual sites; each farmer's trial represented a replicate in the multi-locational experimental design.

The design was adjusted in 2017. The maize- and cassava-targeted fertilizer regimes (FM and FC) formed two independent sets of trials. Due to the better performance of cassava at high density (HC: 12,500 plants ha^{-1}), the low-density (LC: 10,000 plants ha^{-1}) farmer practice (LC-LM-F0) was replaced in the second cycle with a new control treatment; (1) 12,500 cassava and 20,000 maize plants ha^{-1} without fertilizer (HC-LM-F0). Treatments (2) HC-HM-F0, (3) HC-HM-FM, and (4) HC-HM-FC were retained. Two other treatments were introduced; 12,500 cassava and 20,000 maize plants ha^{-1} with fertilizer assumed to favour (5) the maize crop (HC-LM-FM) and (6) the cassava crop (HC-LM-FC). Thus, while the FM set comprised of HC-LM-F0, HC-HM-F0, HC-LM-FM, and HC-HM-FM treatments, the FC set comprised of HC-LM-F0, HC-HM-F0, HC-LM-FC, and HC-HM-FC treatments, with HC-LM-F0 and HC-HM-F0 as common treatments between both sets.

2.4. Crop establishment

Maize variety, EVDT-Y 2000 STR C4 (SAMMAZ 35, yellow grain colour) was used in Anambra, Cross River, Ogun, and Oyo States,

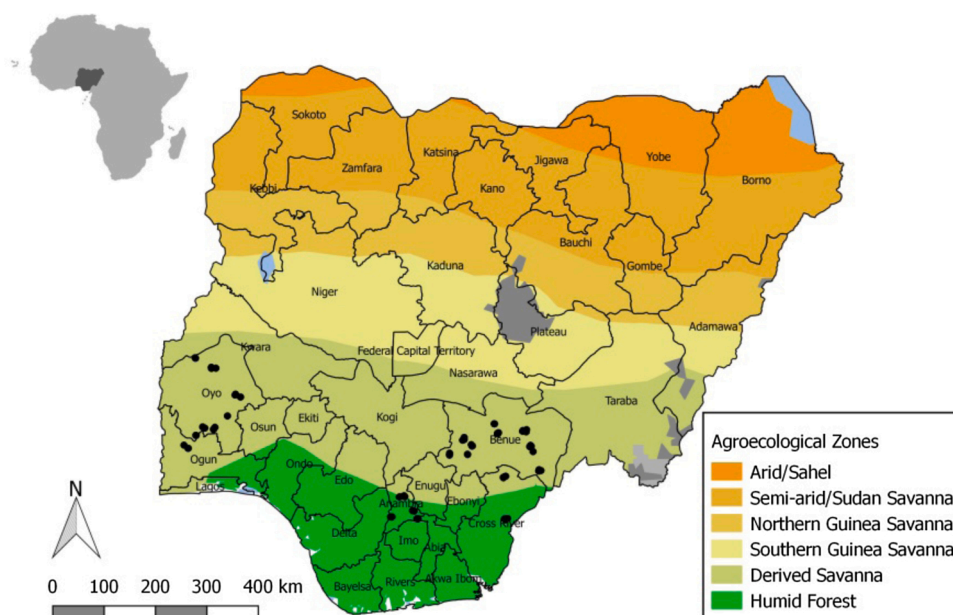


Fig. 1. Distribution of trials across southern Nigeria. Note: dots may represent multiple field locations because trial sites were in close vicinity causing dots to overlap.

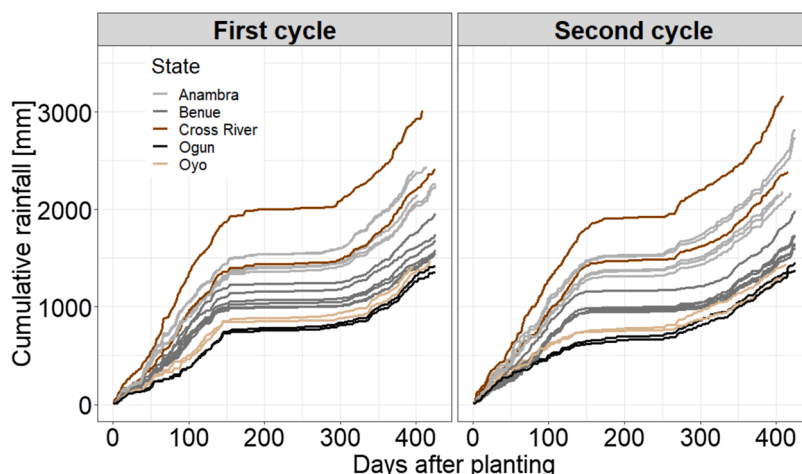


Fig. 2. Cumulative rainfall aggregated by the different local government areas (LGAs) within the states where trials were conducted during the first and second cassava growing cycle. Source: CHIRPS (2020).

Table 1

Combination of the levels of studied factors in the cassava-maize intercropping treatments in the two growing cycles.

Treatments in the first cycle	LC-LM-F0	HC-HM-F0	HC-HM-FM	HC-HM-FC	HC-LM-F0	HC-LM-FM	HC-LM-FC
Treatments in the second cycle		HC-HM-F0	HC-HM-FM	HC-HM-FC			
Cassava planting density ha ⁻¹	10,000	12,500	12,500	12,500	12,500	12,500	12,500
Maize planting density ha ⁻¹	20,000	40,000	40,000	40,000	20,000	20,000	20,000
NPK rates in kg ha ⁻¹ in the first cycle	0:0:0	0:0:0	90:20:37	75:20:90	0:0:0	90:20:37	75:20:90
NPK rates in kg ha ⁻¹ in second cycle	0:0:0	0:0:0	90:20:37	90:20:90	0:0:0	90:20:37	90:20:90

LC = low cassava density; HC = high cassava density; LM = low maize density; HM = high maize density; F0 = no fertilizer; FC = fertilizer targeted at cassava; FM = fertilizer targeted at maize.

whereas variety, EVDT-W 99 STR and 2011-TZE-W DT STR Synthetic (SAMMAZ 27 and 48, white grain colour) was used in Benue State in the first and second cycle, respectively. The maize variety was changed in the second cycle in Benue State due to observed “witchweed” (*Striga asiatica* (L.) Kuntze) attack in the first cycle. The maize varieties were chosen according to farmers’ colour preferences and market acceptability. All maize varieties were early maturing (90–95 days) to limit competition between cassava and maize over time. Cassava variety TME 419 was used in all States except in Anambra where the farmers preferred TMS 98/0581 and in Benue state where the variety TMS 98/0505 was used in the farmers’ practice control treatment (LC-LM-F0) in the first cycle. Both cassava varieties were chosen by the farmers based on popularity and acceptance; they are popular for high storage root yield and high dry matter content.

Cassava and maize were planted on either mechanically or manually prepared one-meter parted ridges arranged across field slopes. In Ogun and Oyo States, some farmers preferred to plant cassava on flat fields after disc plough tillage. Planting patterns on flat fields were the same as on ridged fields. Treatment plots measured 7.2 m in the direction of tillage (ridging) and had 7 rows to give a net plot area of 7 × 7.2 m (14 × 14.4 m per trial), except for the LC-LM-F0 treatment plots in the first cycle which measured 7 m in tillage direction and 7 rows, to give a net plot area of 7 × 7 m (14 × 14 m per trial).

Cassava and maize were planted simultaneously in both cycles. Healthy cassava planting stakes of 20–25 cm length, with a minimum of 5 viable buds were inserted to ¾ of their length into the soil at an angle of approximately 45° along ridge crests or following a line on flat fields. Maize was sown with two seeds per position at mid-slope of ridged fields, 25–30 cm away from the cassava stakes and exactly in the middle between cassava rows (50 cm from cassava) on flat fields. Germinated maize was thinned to one plant per position 2–3 weeks after planting (WAP).

The net plot for maize comprised of the 4 internal rows of 5 m and

5.25 m in length corresponding to an area of 20 and 21 m² in the LM and HM density treatments, respectively. The net plot for cassava comprised of the 5 internal rows of 5 and 5.6 m in length corresponding to an area of 25 and 28 m² in LC and HC density plots, respectively.

2.5. Fertilizer application and management

2.5.1. Fertilizer application and management for the first cycle

The fertilizer targeting the maize crop (FM) was applied to the left of the maize rows. At planting, 300 kg ha⁻¹ NPK 15:15:15 equivalent to 45 kg N, 20 kg P, and 37 kg K ha⁻¹ were applied. Two equal amounts of 50 kg urea ha⁻¹ (22.5 kg N ha⁻¹) were top-dressed at 3 and 6 WAP. The holes for the NPK dosage per hill were approximately 5 cm deep and located in the mid-slope between cassava and maize planting positions; approximately 5 cm next to the maize hills. Following the application, the holes were covered with soil. N top-dressing as urea at 3 and 6 WAP was done by making shallow ditches 10 cm away from maize plants along the ridges in the direction of tillage, and the urea dosage was evenly distributed along the ditch and covered with soil.

In the FC regime, the early fertilizer dressings were applied next to the maize rows at a 10 cm distance, the later dressings were applied close to the cassava. Application of 300 kg ha⁻¹ NPK 15:15:15 equivalent to 45 kg N, 20 kg P, and 37 kg K ha⁻¹ at 2 WAP and 15 kg N ha⁻¹ as urea at 6 WAP followed a similar procedure as in the FM regime. At 10 WAP, N (15 kg urea ha⁻¹) and K (25 kg MoP ha⁻¹) were top-dressed by scooping 1 m long shallow ditches along the crests of ridges starting approximately 10 cm away from the cassava stakes and placing the fertilizers, and hereafter covering with soil. Application of the last dressing of K (28 kg MoP ha⁻¹) at 16 WAP followed the same procedure.

2.5.2. Fertilizer application and management for the second cycle

Urea top dressing in the FM regime was applied at 5 WAP instead of at 6 WAP. This was due to our observation that application at 6 WAP

coincided with the onset of the maize reproductive phase i.e., anthesis. However, the remaining applications of the fertilizers in the FM regime followed the 2016 procedures.

In the FC regime, all P was applied as triple superphosphate (TSP) at 0 WAP. Twenty percent (15 kg N ha^{-1}) of total N in the regime was applied at 0 WAP to satisfy an early N requirement of maize. This was followed by N and K in 3 dressings which involved the application of 30 and 27 kg ha^{-1} of urea and MoP at 4 WAP. The remaining amount of N and K was applied in 2 equal dressings as urea and MoP at 22.5 and 35.5 kg ha^{-1} , separately at 11 and 17 WAP.

2.6. Crop protection

Fall armyworm (*Spodoptera frugiperda*) infestation was controlled on maize plants by spraying with a mixture of Ampligo (active ingredient *chlorantraniliprole*) at a dosage of 15 ml per 15-liter knapsack spray volume. Spraying targeted the maize funnels to ensure direct contact with the adult moths, eggs, and/or larvae. Ampligo application was repeated as required by the reappearance of army-worm attacks. In Anambra State, termite (*Isoptera*) infestation was controlled by treating planting stakes with a mixture of Termex (active ingredient *imidacloprid*) by soaking planting stakes for 30 min in a solution of 10.5 ml Termex in 5 L of water before planting. Weeds were manually controlled by the farmer using a hand hoe.

2.7. Maize and cassava harvest

In 2016, maize was harvested at physiological maturity at about 12–13 WAP. In 2017, maize was harvested earlier at the dough stage, at about 10–11 WAP due to the farmers' preference to collect fresh cobs for consumption and sales. Maize harvest started with the removal of the border rows. Maize plants were counted and cobs were removed from all net plot plants. Cobs were separated according to their quality into marketable and non-marketable, whereby diseased and damaged cobs were classified as non-marketable. In a companion researcher-managed trial (Nwokoro et al. 2021, in prep) grain yield equivalent of the marketable cobs were determined. During the cob yield assessment, the cobs were grouped into different size categories; big, medium, small, and unfit. This was specifically done to ensure that cob sampling for grain yield determination was a representation of cob yield in each treatment. For the grain yield equivalent of the cobs, we used weighted means of each of the cob categories per treatment to calculate the grain yield equivalent based on the grain yields from each category. Subsequently, the grain dry matter (DM) content was calculated; on average, 1 cob was equivalent to 103 g of grain. However, we reported maize yield in numbers of marketable cobs ha^{-1} because this was how our collaborating farmers sold maize; this practice is especially common in Southern Nigeria. Per protocol, after cob harvest, the stover was to be laid along in the furrow within each plot. However, some farmers carted away the stover and fed it as fodder to animals, for example, goats.

Cassava was harvested between 12 and 15 months after planting (MAP). Fresh storage root yield was assessed from the net plots. All net plot plants were uprooted, and roots were cut off the planting stakes, counted, and weighed. Roots of a diameter $> 1.5 \text{ cm}$, without diseases or rot, were regarded as marketable. The cassava root yield was expressed as fresh root yield (Mg ha^{-1}).

2.8. Economic analysis of investment in fertilizer, and net revenue

A financial analysis to evaluate the profitability of fertilizer use in cassava-maize intercropping was done by comparing returns to investment in fertilizer against the control treatment. The purchasing price of mineral fertilizers was obtained from an agro-dealer in Anambra State. The total cost for each fertilizer regime (FM and FC) was calculated. The NPK 15:15:15 compound fertilizer sold for 0.40 USD kg^{-1} . N as urea, P as TSP, and K as MoP fertilizers were sold for 0.44, 0.50, and 0.66 USD

kg^{-1} , respectively. Prices of fresh cobs and fresh storage roots were obtained from the local market in Anambra State and equalled 0.06 USD per cob and 40 USD Mg^{-1} of fresh storage roots. Revenue derived by the increases in cob and storage root yields in response to fertilizers application relative to the control treatment was regarded as net benefits. The value cost ratio (VCR), an economic indicator for cost-benefit analysis was calculated for each of the fertilizer treatments as the gross revenue increase over the cost of purchased fertilizers. An investment in fertilizer is considered profitable for smallholders if the VCR exceeds 2 USD USD^{-1} ; VCR values between 1 and 2 USD USD^{-1} are considered risky investments, and values less than 1 imply a loss in income.

Trade-offs in net revenue in storage root and marketable cob yields were compared using the actual data and under varied scenarios of increasing or decreasing the market prices of cassava storage roots, maize marketable cobs, and fertilizers by 50 % for selected treatments (HC-HM-FM and HC-LM-FC) due to the relative peculiarity of higher marketable cob and storage root yields in those treatments. The net revenue from storage roots and marketable cobs relative to HC-HM-F0 was calculated and plotted against each other.

2.9. Statistical analysis and data visualization

All statistical analyses were done using the linear mixed-effects ('lme4') (Bates et al., 2015) and the analysis of variance model ('aov()') (Chambers et al., 1992) commands in the Rstudio environment (R Core Team, 2020). Figures for data visualizations were plotted in the Rstudio using the 'ggplot2()' data visualization package (Gómez-Rubio, 2017).

Analysis of variance was carried out to determine the effects of planting densities (maize and cassava) and fertilizer application rates (and their interactive effects) using the mixed effect model. Four (C-LM-F0, C-HM-F0, C-HM-FC, and C-HM-FM) and six (C-HM-F0, C-HM-FC, C-HM-FM, C-LM-F0, C-LM-FC, and C-LM-FM) treatments of the maize and fertilizer factor combinations were independently analysed in the first and second cycle, respectively. For this, the individual combination of factors (regarded as treatments) was the fixed effect factor, and fields of the individual farmers were the random effect factors. To determine the effects of the fertilizer and maize levels, common treatments of both cycles were pooled and analysed as a two-way ANOVA, comparing two levels of maize density and three levels of fertilizer. The maize and fertilizer levels (and their interaction) were the fixed factors while farmers' fields were the random effect variable.

After the computation of the VCR, a simple analysis of variance was carried out whereby the VCR and the fertilizer regimes were the response and predictive variables, respectively. The significance of differences was evaluated at $P \leq 0.05$ and $P \leq 0.01$.

3. Results

3.1. Biophysical characteristics of the study area

In about 90 % of the LGAs, the total amount of rainfall in the first cycle was slightly less than in the second cycle (Fig. 2). There was higher rainfall in the Humid Forest than in the Derived Savanna. In the Derived Savanna, rainfall ranged from 1351 to 2339 mm and 1372–2430 mm in the first and second cycle, respectively. In the Humid Forest rainfall ranged between 2241 to 3222 mm and 2321 to 3438 mm in the first and second cycles. Average rainfall was 1720 and 1747 mm in Derived Savannah and 2604 and 2744 mm in Humid Forest during the cassava average growing season of 428 days in the first and second cycles, respectively.

All soil parameters differed between states. In general, SOC ranged between 1.1 to 2.1 %, pH (in 1:2.5 H_2O) 5.1 to 6.3, total N 0.5 to 1.4 g kg^{-1} , total P 4.2 to 15.4 mg kg^{-1} , and exchangeable K 0.9 to 1.8 cmol kg^{-1} (Table 2). The SOC and total N were higher in Anambra, Cross River, and Ogun States; Oyo and Benue States had the lowest

concentrations according to the soil grid data. The exchangeable K content was higher in Ogun, Oyo, and Benue States. In general, Oyo and Ogun States had higher sand contents. Clay content was higher in Cross River and Anambra; Oyo, Ogun, and Benue had the least. Fields in Anambra State had the lowest silt content, while those in Benue, Cross River, and Oyo States were found to have the highest.

3.2. Maize marketable cob and cassava storage root yields

There was no difference ($p = 0.28$) in the overall marketable maize cob yield between the first and second cycles. In both cycles (2016 and 2017), the marketable cob yield was significantly increased ($p < 0.01$) due to increased maize plant density and fertilizer application (Fig. 3). Furthermore, fertilizer application increased ($p < 0.01$) the marketable cob yield, regardless of maize density. Increased maize planting density without fertilizer application (HM-F0) in the first and second cycle increased the number of marketable cobs by 14 % (3700 cobs ha⁻¹) and 8 % (2100 cobs ha⁻¹), respectively, compared to LM:F0 (Fig. 3). At conditions of low maize (LM) plant density, the application of FC regime increased ($p < 0.01$) marketable cob numbers by 11 % (2958 cobs ha⁻¹); 8 % (2637 cobs ha⁻¹) less than the effect of the FM regime. A

Table 2
Variation in soil physicochemical properties of SoilGrids data at 0–30 cm depth across states.

State	Parameter	Min	Max	Mean	SEM
Anambra	pH (1:2.5 H ₂ O)	5.1	5.4	5.3	0.01
	Organic carbon (%)	1.1	2.1	1.5	0.03
	Total N (g kg ⁻¹)	0.8	1.4	1.1	0.02
	P (mg kg ⁻¹)	8.2	12.0	10.2	0.1
	Exch. K (cmol kg ⁻¹)	0.9	1.7	1.1	0.02
	Sand (%)	56.0	69.0	63.0	0.3
	Silt (%)	9.0	16.0	13.5	0.1
	Clay (%)	21.0	28.0	23.3	0.2
Benue	pH (1:2.5 H ₂ O)	5.5	5.8	5.6	0.006
	Organic carbon (%)	0.9	1.4	1.1	0.009
	Total N (g kg ⁻¹)	0.5	1.0	0.7	0.1
	P (mg kg ⁻¹)	4.4	10.8	6.8	0.1
	Exch. K (cmol kg ⁻¹)	0.7	1.4	0.9	0.08
	Sand (g kg ⁻¹)	56.0	72.0	63.9	0.3
	Silt (g kg ⁻¹)	15.0	23.0	18.1	0.1
	Clay (g kg ⁻¹)	13.0	23.0	18.0	0.2
Cross River	pH (1:2.5 H ₂ O)	5.1	5.5	5.3	0.02
	Organic carbon (%)	1.1	2.1	1.3	0.03
	Total N (g kg ⁻¹)	0.7	1.4	1.1	0.1
	P (mg kg ⁻¹)	7.7	15.3	9.5	0.2
	Exch. K (cmol kg ⁻¹)	0.8	1.8	1.3	0.05
	Sand (%)	55.0	59.0	56.5	0.1
	Silt (%)	14.0	21.0	17.5	0.2
	Clay (%)	23.0	30.0	26.0	0.3
Ogun	pH (1:2.5 H ₂ O)	5.9	6.1	5.9	0.02
	Organic carbon (%)	1.2	1.4	1.3	0.02
	Total N (g kg ⁻¹)	0.7	1.2	1.1	0.5
	P (mg kg ⁻¹)	6.6	10.8	9.8	0.5
	Exch. K (cmol kg ⁻¹)	1.1	1.2	1.1	0.01
	Sand (%)	64.0	72.0	66.0	1.0
	Silt (%)	14.0	16.0	15.2	0.2
	Clay (%)	16.0	21.0	19.6	0.6
Oyo	pH (1:2.5 H ₂ O)	5.8	6.3	5.9	0.01
	Organic carbon (%)	1.0	1.2	1.1	0.005
	Total N (g kg ⁻¹)	0.6	0.9	0.7	0.06
	P (mg kg ⁻¹)	5.3	13.6	8.0	0.2
	Exch. K (cmol kg ⁻¹)	0.9	1.3	1.1	0.07
	Sand (%)	60.0	75.0	67.8	0.3
	Silt (%)	11.0	20.0	15.8	0.2
	Clay (%)	13.0	21.0	16.3	0.1

SEM: standard error of the mean.

(Source: ISRIC, 2020).

similar trend was maintained at conditions of HM plant density; the number of marketable cobs ha⁻¹ increased by 15 % (4960 cobs ha⁻¹) under the FC regime, which was 4 % (1749 cobs ha⁻¹) less compared to the effect of the FM regime at conditions of HM plant density. No interaction effect of maize density and fertilizer was observed (Table 3).

Overall average storage root yield was 16 Mg ha⁻¹ in the first cycle, 15 % (4 Mg ha⁻¹) higher than the average storage root yield (12 Mg ha⁻¹) in the second cycle. Without fertilizer application, increasing cassava planting density (10,000–12,500 plants ha⁻¹) increased storage root yield by 16 % (4 Mg ha⁻¹) in the first cycle (Fig. 3). Similarly, fertilizer application at HC also increased storage root yield by 14 % (4 Mg ha⁻¹) in the first cycle. Without fertilizer application, the high maize plant density reduced ($p < 0.01$) cassava storage root yield by 7 % (1.5 Mg ha⁻¹) in the second cycle (Fig. 3). With fertilizer application, however, no storage root yield reduction was observed. The effects of the FC and the FM regimes on cassava storage root yield were similar: both increased storage root yield by 8 % (2 Mg ha⁻¹) relative to no fertilizer application. No interactive effect of maize density and fertilizer application was observed on storage root yield (Table 3).

3.3. Effects of fertilizer application

To examine cassava and maize yields responses to fertilizer application across fields, individual effects of the fertilizer regimes (FM and FC) were plotted against the yield in the control treatment for the two cycles. Although there was a generally positive response to both fertilizer regimes by marketable cobs, as the majority of the observations lie above zero (Fig. 4), there was a very weak non-significant negative association between marketable cobs responses versus yields in control treatment with the FC regime in the first cycle. Similarly, there was a non-significant weak positive association between marketable cob responses and the control yields with the FM regime in the first cycle. In the second cycle, there were significantly ($p < 0.05$) weak negative associations of responses of number of marketable cobs ha⁻¹ versus control yields with either of the fertilizer regimes. Storage root yield responded differently to fertilizer application compared to the marketable cobs; it appears that in both cycles, the response of storage root yield was greater when yield in the control treatment was small; non-responsive situations occurred more frequently when control yields were ≥ 20 Mg ha⁻¹ (Fig. 4). There were significant strong (with FC) and weak (with FM) negative associations between storage root responses and control yields without fertilizer application in the first cycle. In the second cycle, the relationships were non-significantly ($p > 0.05$) weak associations with either of the fertilizer regimes (Fig. 4).

3.4. Cost-benefit ratio of investment in fertilizer and net revenue trade-offs in cassava-maize intercrop

An average VCR of 3.6 USD USD⁻¹ was obtained for the FM regime with a range from -5 to 13.2, while the FC regime VCR was significantly ($p < 0.001$) lower at an average of 1.6 USD USD⁻¹ and ranging from -3 to 7 (Fig. 5 a). The result of the cumulative probability showed that 33 % and 46 % of the farmers lost income (VCR < 1 USD USD⁻¹) by investing in the FC NPK fertilizers regime in the first and second cycle, respectively, whereas 24 % and 31 % of the farmers lost income by investing in the FM NPK regime in the first and second cycle (Fig. 5 b). While 11 % and 29 % of farmers gained but did not double investment ($1 \leq \text{VCR} \leq 2$) in the FC regime in the first and second cycle, respectively, 56 % and 25 % of farmers doubled investment and more ($\text{VCR} \geq 2$ USD USD⁻¹) by investing in the FC fertilizer regime in the first and second cycle, respectively. Under the FM regime, 8 % and 11 % of the farmers gained but not up to a double of investment cost ($1 \leq \text{VCR} \leq 2$) in the first and second cycle, respectively, and 68 % and 57 % of the farmers at least doubled the return of investment ($\text{VCR} \geq 2$) in the first and second cycle.

The net revenue gained through increases in storage root and marketable cob yields showed a consistent trend across the different

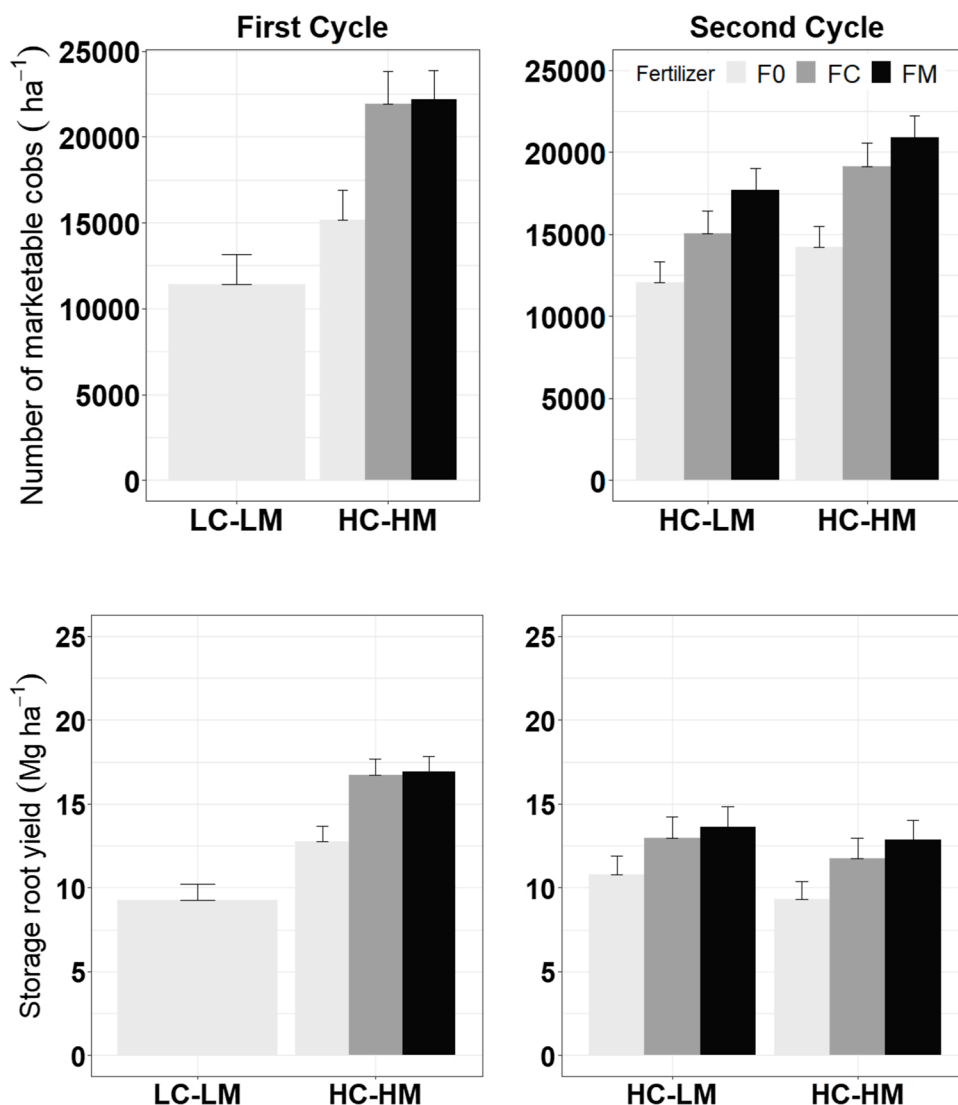


Fig. 3. Effect of maize and cassava planting density and NPK fertilizer application on the number of marketable maize cobs and cassava fresh storage root yields in cassava-maize intercropping system during two cropping cycles. LC: low density cassava (10,000 ha⁻¹); HC: high density cassava (12,500 ha⁻¹); LM: low density maize (20,000 ha⁻¹); HM: high density maize (40,000 ha⁻¹); F0: no fertilizer applied; FM: fertilizer application at 90 kg N ha⁻¹, 20 kg P ha⁻¹ and 37 kg K ha⁻¹; FC: fertilizer application at 75 kg N ha⁻¹, 20 kg P ha⁻¹ and 90 kg K ha⁻¹ in the first cycle and 90 kg N ha⁻¹, 20 kg P ha⁻¹ and 90 kg K ha⁻¹ in the second cycle. Error bars represent standard errors of the mean.

Table 3
Analysis of variance of treatments imposed during the experimental cycles.

	Maize cob			Cassava storage root		
	First cycle Pr(>F)	Second cycle Pr(>F)	Factorial Pr(>F)	First cycle Pr(>F)	Second cycle Pr(>F)	Factorial Pr(>F)
Overall Treatment effect*	0.00***	0.00***	—	0.00***	0.00***	—
<i>Factorial analysis **</i>						
Maize density	—	—	0.00***	—	—	0.00***
Fertilizer	—	—	0.00***	—	—	0.00***
Maize density × Fertilizer	—	—	0.32	—	—	0.85

* Treatments in the first cycle: LC-LM-F0, HC-HM-F0, HC-HM-FC, and HC-HM-FM. Treatments in the second cycle: HC-LM-F0, HC-LM-FC, HC-LM-FM, HC-HM-F0, HC-HM-FC, and HC-HM-FM.

** Factors: 2 levels of maize density (LM and HM) and 3 levels of fertilizer (F0, FC, and FM).

scenarios (Fig. 6). With our actual data, only the treatment of high maize density under a management of FM regime (HC-HM-FM) turned a profit from investment in fertilizer. Regardless of maize density and fertilizer regime, when a 50 % price reduction was assumed for either the cassava storage root price (CP) or the maize cob price (MP) at constant fertilizer prices (FP), a negative net revenue was always realized. On the contrary, an increase in MP by 50 %, when the other variables (CP and FP) remained constant, resulted in a positive net profit of 156 USD ha⁻¹ at

low maize density under the FC regime (HC-LM-FC). In the high maize density treatment, the 50 % increase in MP turned the highest profit under the FM regime (834 USD ha⁻¹). On the other hand, net profits were obtained at HM planting only under the FM regime when either the CP or the FP was increased by 50 % or when the FP was reduced by 50 %. Except for situations where the MP was increased by 50 % for HC-LM, the FC regime resulted always in negative net revenue.

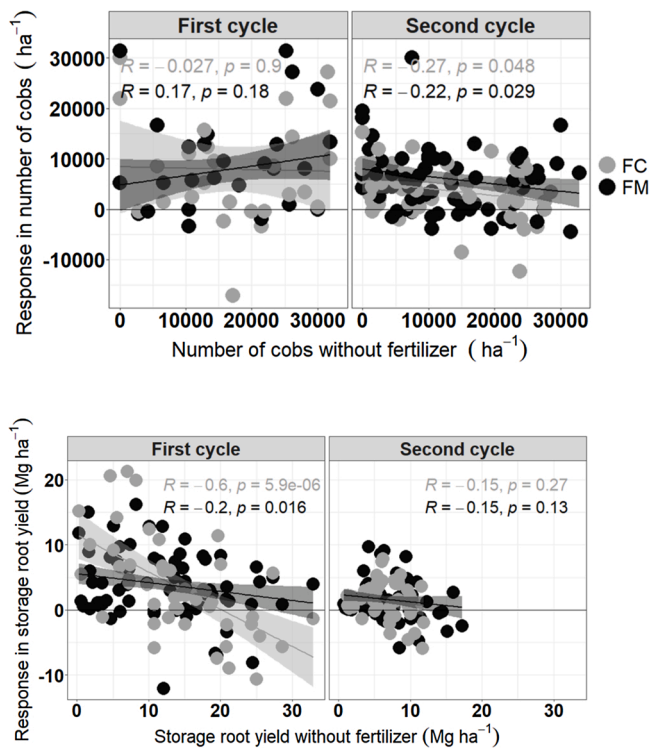


Fig. 4. Maize cob yield and cassava storage root yield response due to fertilizer application versus control yield (without fertilizer application) in on-farm field trials during two cropping cycles. **FM:** fertilizer application at 90 kg N ha⁻¹, 20 kg P ha⁻¹ and 37 kg K ha⁻¹; **FC:** fertilizer application at 75 kg N ha⁻¹, 20 kg P ha⁻¹ and 90 kg K ha⁻¹ in the first cycle and 90 kg N ha⁻¹, 20 kg P ha⁻¹ and 90 kg K ha⁻¹ in the second cycle. The regression line for second cycle storage root yield in FC regime is obscured by the nature of the data distribution.

4. Discussion

4.1. Effect of planting density and fertilizer application on marketable cobs and fresh storage root yields

Without fertilizer application, increasing cassava and maize densities increased marketable maize cob yield in both cycles and cassava storage root yield in the first cycle. Although there are reports of reduced crop yields at increased planting density both in sole cropping and intercropping situations (Muoneke and Asiegbu, 1997), such reports reflected mostly a situation where the optimal planting density was exceeded. Similar to our result, some research reports that crop yields can be improved by increased planting density as long as the optimal planting density at any growing condition is not exceeded (Asiimwe et al., 2016; Egbe and Idoko, 2009; Muoneke, 2007). The average storage root yield (14 Mg ha⁻¹) in our study exceeded the average reported yield by Ezui et al. (2016) or in the cassava-maize intercropping study by Joseph et al. (2018), and is equivalent to what was reported by Olasantan et al. (1997). However, our average marketable cob yield (16, 800 cobs ha⁻¹) was similar to the yields reported by Joseph et al. (2018) and Olasantan et al. (1997) in cassava-maize intercropping studies, albeit at lower cassava (10,000 plants ha⁻¹) and a similar maize (40,000 plants ha⁻¹) plant density. When the seeding rate is increased, crop growth, development, and yield are modified, and in most cases to the detriment of single crop performance, but, due to a higher number of plants per unit area at high-density situations, final yields are improved.

In the second cycle when cassava was intercropped with maize at high plant density (HM) without fertilizer application, storage root yield was slightly reduced by 7% (1.5 Mg ha⁻¹). Similar yield reduction effects by maize and other short-duration intercrops on cassava storage root yield in intercropping systems were reported by Cempukdee and

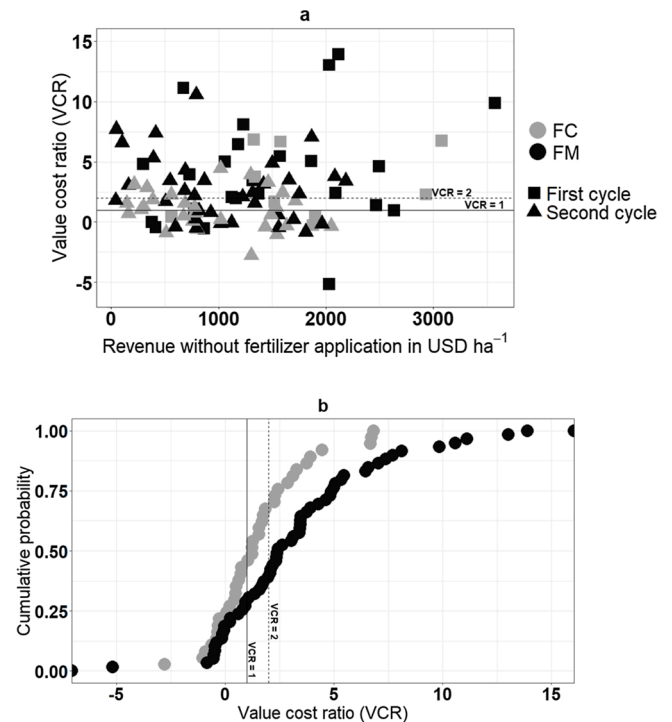


Fig. 5. The relationship between the effect of fertilizer application on the combined value cost ratio (VCR) from cassava storage root (Mg ha⁻¹) and marketable cob (ha⁻¹) yields and the combined revenue from the yields of both crops without fertilizer application (in control treatment) in the first and second cycle (a), and cumulative probability frequency effects of the FM and FC regimes in cassava-maize intercropping system in both (first and second) cycles. **FM:** fertilizer application at 90 kg N ha⁻¹, 20 kg P ha⁻¹ and 37 kg K ha⁻¹; **FC:** fertilizer application at 75 kg N ha⁻¹, 20 kg P ha⁻¹ and 90 kg K ha⁻¹ in the first cycle and 90 kg N ha⁻¹, 20 kg P ha⁻¹ and 90 kg K ha⁻¹ in the second cycle.

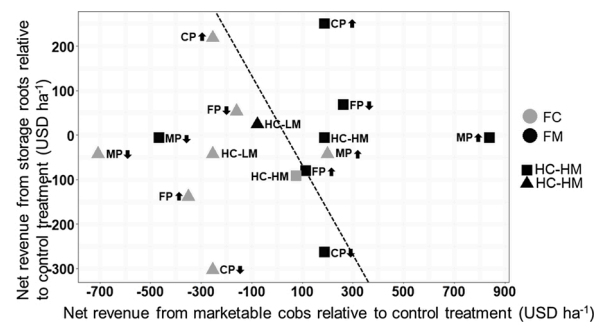


Fig. 6. Effect of maize density and NPK fertilizer on net revenue (USD ha⁻¹) trade-off from storage roots and marketable cobs yields in cassava-maize intercropping system. The dotted line indicates no net revenue (and with left a negative and right a positive net revenue) for the cassava-maize intercropping system as a whole. **CP:** cassava price; **MP:** maize price; **↑:** price increase by 50%; **↓:** price reduction by 50%; **FP:** fertilizer price; **FM:** fertilizer application at 90 kg N ha⁻¹, 20 kg P ha⁻¹ and 37 kg K ha⁻¹; **FC:** fertilizer application at 75 kg N ha⁻¹, 20 kg P ha⁻¹ and 90 kg K ha⁻¹; **HC-HM:** cassava-maize intercropping at 12,500 cassava and 40,000 maize plants ha⁻¹; **HC-LM-FC** and **HC-HM-FM** due to the higher yield performance of cassava and maize in the treatments respectively.

Fukai (1992); Joseph et al. (2018), and Olasantan et al. (1996). Other studies (Adeniyani and Ayoola, 2007; Olasantan et al., 1996) reported larger cassava root yield reductions, probably due to the use of longer-duration maize varieties, as compared with the short duration

varieties used in our study. In general, these observed reductions in cassava yield could be a result of the poor competitive ability of the cassava plant at the early stage of growth when intercropped with maize, especially at high density. Indeed, the first 3–4 months of cassava growth is described as a period of slow growth and reflects a time when cassava would compete poorly with intercropped plants (Olasantan et al., 1994; Silva et al., 2016). Maize, on the other hand, is a faster-growing crop compared to cassava, completing its life cycle within 3–4 months (Plesis et al., 2003). If different species of crops are intercropped, the component which has a higher density and possesses greater competitive ability tends to out-compete the other crop for available resources (Gou et al., 2016). Maize is fast in development and has an extensive rooting system such that if grown under relatively good conditions (i.e., adequate moisture and nutrients), it can compete for available growth resources (Plesis et al., 2003; Testa et al., 2016) under intercropping situations (Adeniyani et al., 2014). However, regardless of maize density at intercropping with cassava, fertilizer application counteracted part of the storage root yield reduction effect. Olasantan et al. (1996) also reported that nutrient management in cassava-maize intercropping systems strongly enhanced the ability of cassava to overcome the detrimental effects of intercropping during early crop growth.

Regardless of maize plant density, fertilizer application increased the number of marketable maize cobs and cassava storage root yields. As is well-known, most tropical soils lack important nutrients required to sustain or improve crop yield (de Moura et al., 2016) as indicated also by the soil grid data of our trial locations (Table 2). Hence, N, P, and K fertilizer application can improve crop yields (Yousaf et al., 2017) and many studies have indeed reported the beneficial effects of NPK fertilizers on the yields of cassava and maize, either as sole crops or when intercropped (Adeniyani et al., 2014; Ezui et al., 2017; Munyahali, 2017; Olasantan et al., 1994; Kreye et al., 2020).

Fertilizer effects on maize and cassava yields were, however, regime-specific, particularly for the maize crop. Regardless of maize density, the FM regime, leading to a higher N application rate, resulted in a higher marketable cob yield than the FC regime. Our result corroborates many previous reports on the positive effects of nitrogen on maize performance (Băşa et al., 2016; Saïdou et al., 2003). Furthermore, the N rate in FM was not only higher than the rate in the FC regime especially in the first cycle but it was also applied earlier to the maize, which most likely improved plant establishment and early growth. The N rate in the FM regime was similar to the N recommendation by Saïdou et al. (2018) for maize production. Interestingly, there were no apparent differences in storage root yield between the two fertilizer regimes, contrary to our expectation that the FC regime would result in higher storage root yield because of the higher K rate. Seemingly the K levels (0.9 to 1.8 cmol kg⁻¹) at our trial sites (Table 2), although mostly below the minimum required level (1.5 to 2.5 cmol kg⁻¹) for cassava production (Howeler, 2002), may not have been low enough to cause apparent differences in storage root yield between the two fertilizer regimes (Figs. 3 and 4), despite differences in K rate (37 kg K ha⁻¹ for FM and 90 kg K ha⁻¹ for FC). Possibly also, the soils may have adequate K stocks in the deeper soil layers. In contrast to our findings, Adiele et al. (2020) reported a higher storage root yield at a K application rate of 180 kg ha⁻¹ in similar environments in Nigeria; an indication that perhaps the K rates we tested in our study were mostly below the K requirements of our trial sites.

4.2. Variations in response to fertilizer application

Response to NPK application varied across sites in both cycles. When either the storage root or the marketable cob yields with either of the fertilizer regimes were plotted against yields from the control (treatment without fertilizer application), we observed that the majority of the fields have positive responses, but more so when control yields were low (Fig. 4). Qiu et al. (2014) reported also progressive yield differences in maize grain and stover yields as the fertility levels widened between the

unfertilized and fertilized treatments. Similarly, Fermont et al. (2010) reported responses to fertilizer to vary across different locations and indeed decrease on more fertile soils. Nevertheless, it is important to note that particularly for the cassava storage root, the yield response to fertilizer was low and negatively correlated with control treatment especially at high control yields, resulting in average fertilizer response becoming close to absent (Fig. 4). A similar result on storage root response to fertilizer application was reported by Munyahali et al. (2017) in a study conducted in the province of South Kivu, DR Congo. The variations in control yields and yield responses are likely at least partially a reflection of the effects of the variations in the soil properties of our study fields (Table 2; Fig. 4). Except for pH (5.1–6.3 in 1:2.5 H₂O) and available P (4.2–15.4 mg kg⁻¹), the range in values of all soil chemical parameters were below the minimum requirements (SOC 2.0%–4.0%, available P 4.0–15.0 mg kg⁻¹ and exchangeable K 1.5 to 2.5 cmol kg⁻¹) for cassava (Howeler, 2002) and maize (Ayodele and Omotoso, 2008) production (Table 2). The yield variation could also be attributed to the observed variations in the total amount of rainfall received throughout the crop growth (Fig. 2), previous fertilizer management, fallow period and overall crop management. In a study conducted in Kiduma and Mbuele, both in DR Congo, Pypers et al. (2012) found residual effects of previously applied fertilizers on cassava root yield in the following year. Although both fertilizer regimes targeted specific crops (FM at maize and FC at cassava), their nutrient ratios are similar to the recommendations by Ezui et al. (2016) for cassava and NAAS (2009) for maize. However, the intercropping of both crops might have confounded yield responses; it could be that because the maize matured and was harvested much earlier than the cassava, it experienced less competition for nutrients from the cassava hence, the fewer negative cob yield responses in comparison to the cassava. As explained earlier, K can become a yield limiting nutrient in cassava production. The fact that the highest K concentration in maize is found in the stover (Bağ et al., 2016) could also explain the more negative yield responses of storage root due to the inconsistencies of stover management at different fields. Most of our participating farmers removed and fed the stover to livestock rather than returning them to the plots, thereby reducing the amount of K available to cassava.

4.3. The effect of fertilizer application on value cost ratio and net revenue

Because the maize marketable cob yields were higher under the FM regime at high maize density, VCR values from high maize density treatments were always higher than their low-density maize counterparts. It is widely considered that a VCR should be ≥ 2.0 , especially in a developing economy (such as Nigeria) to provide incentives for fertilizer use and overcome risks and costs of capital investment (CIMMYT, 1988; Munyahali et al., 2017; Sommer et al., 2013). Both the FM and FC regimes generated in over half of the trials a VCR exceeding 2.0 USD USD⁻¹ in both cycles (Fig. 6 a). A similar result on VCR (or a benefit-cost ratio (BCR)) ≥ 2.0 with fertilizer application was reported by Thandar (2014) for cassava intercropped with either cowpea, groundnut, or soybean, and by Senkoro et al. (2018) for sole cropped cassava in Tanzania, Kenya, and Ghana. The variations we observed in the VCR figures were due to differences in response to fertilizer across different fields (Fig. 4), possibly as a result of variation in soil properties as explained earlier. Our findings corroborate results by Munyahali et al. (2017) who reported variations in VCR values as a result of variations in soil qualities using cassava as a test crop. While under the FC regime 33 % and 46 % of farmers lost money due to investment in NPK fertilizers in the first and second cycle, respectively, the FM regime led to 24 % and 31 % of farmers losing money in the first and second cycles (Fig. 6 b). The FM regime always led to a higher VCR than the FC regime. This is mostly due to higher yields of maize cobs under FM than the FC regime because storage root yields were comparable across the two fertilizer regimes. Interestingly, Senkoro et al. (2018) reported a linear cassava yield increase along with increased rates of N application that resulted in

VCR > 2 at all trial locations in Tanzania, Kenya, and Ghana compared with increased rates of P and K observed only in Ghana. According to our results, it is, however, riskier to invest in the FC regime than the FM in cassava-maize intercropping for the conditions in our study. This confirms the report that the most limiting nutrient in tropical soils is N of which an adequate and timely supply results in increased crop yields, and a higher likelihood of profitable returns (de Moura et al., 2016). Perhaps VCR higher than what we obtained could have been achieved had the nutrient ratios in both regimes based on specific site requirements according to soil fertility and exact nutrient requirements of our fields. Ezui et al. (2016) reported less benefit to cost ratio (BCR) with blanket fertilizer application compared to higher BCR with site-specific fertilizer use. This suggests that for higher response and margin in fertilizer use, a decision on nutrients ratios and recommendations should be based on specific site requirements regardless of the cropping system.

We observed no differences in cassava storage root yields between the two fertilizer regimes, and an average increase in storage root yield of 4 Mg ha⁻¹ due to fertilizer application was obtained. Nevertheless, the marketable maize cob yield was 18.4 % (2088 cobs ha⁻¹) lower under the FC than FM regime. Furthermore, the revenue generated by maize cobs constituted 84 % and 91 % of the total revenue under the FC and FM regimes, respectively. Therefore, except in situations where either the fertilizer price reduces or the storage root market price increases by 50 % each, or both happen, it is unlikely that profit can be returned by the intercropping of cassava with low maize density (HCLM) under a management of FC regime (Fig. 6). Hence, there are salient considerations to make when profitability is expected. Such considerations include but are not limited to: i) information on soil fertility to determine if external fertilizer input is necessary, if yes, target yield(s) at which investment in fertilizer is returned should be considered, ii) nutrient ratios of the required NPK fertilizers, iii) the prevailing market prices of produce and fertilizers inputs, and iv) the cassava and maize planting densities.

5. Conclusion

In general, cassava and maize planting densities, as well as fertilizer application had significant effects on the yield of both crops and profitability in the cassava-maize intercropping system. With or without fertilizer application, planting of cassava at 12,500 and maize at 40,000 plants ha⁻¹ would improve yields from both crops in the system compared with planting cassava at 10,000 and maize at 20,000 plants ha⁻¹. However, yields would be generally higher if the system is managed with fertilizer, especially on nutrient limited fields such as the environments of our study. Without fertilizer application, intercropping cassava with maize at 40,000 plants ha⁻¹ would most likely reduce cassava storage root yield by at least 7% or more, depending on the inherent fertility of the field due to high competition for nutrients at higher densities. However, this effect can be counteracted by fertilizer application on nutrient limited fields regardless of maize density, or by planting maize at 10,000 plants ha⁻¹ in situations where fertilizers are not affordable. Should the system be managed with fertilizer in a similar production environment as our study area, 90 kg N, 20 kg P, and 37 kg K ha⁻¹ (the FM regime) is recommended over 75 or 90 kg N, 20 kg P, and 90 kg K ha⁻¹ (the FC regime) due to higher marketable cob yield with the FM and comparable storage root yields compared with the FC regime according to the results we obtained. Nevertheless, responses of storage roots and marketable cobs to fertilizer application varied substantially between sites and were likely related to differences in production factors such as soil fertility, rainfall, crop durations, and nutrients ratios. Therefore, it is advised that decisions on fertilizer nutrient ratios, rates and management should be based on good knowledge of any production environment of interest, especially the inherent soil fertility, rainfall duration and other crop production factors. Generally, fertilizer responses are less, or even negative, on moderate to fertile soils.

The average value to cost ratio (VCR) under the FM regime was 3.6

USD USD⁻¹ and higher than the average VCR (1.6) under the FC regime, an indication that N was perhaps the most yield limiting nutrient in our study environment. The application, in adequate amount, of yield limiting nutrients in every production environment would likely result in higher VCR. By investing in NPK fertilizers in cassava-maize intercropping systems, profitability can be achieved, however, this is contextual as it would depend on agroecology and market prices. According to the results of this study, it is apparent that more research is needed to understand the peculiarities of smallholder farmers' production environments and their specific resources to at least understand under what circumstances are fertilizer investments capable of achieving what level of profitability, since not all the farmers benefited from using fertilizer.

CRedit authorship contribution statement

Charles Chigemezu Nwokoro: Investigation, Data curation, Writing original draft. **Christine Kreye:** Conceptualization, Data curation, Methodology, Investigation, Supervision, Writing – review & editing, Funding acquisition, Project coordination Nigeria. **Magdalena Necpalova:** Methodology, Supervision, Writing – review & editing. **Olojede Adeyemi:** Supervision, Investigation, Writing – review & editing, Project administration. **Mutiu Busari:** Investigation, Writing – review & editing. **Meklit Tariku:** Data curation, Methodology, Writing – review & editing. **Mark Tokula:** Writing – review & editing, Investigation. **Florence Olowokere:** Investigation, Writing – review & editing. **Stefan Hauser:** Data curation, Methodology, Investigation, Writing – review & editing, Funding acquisition, Project administration. **Pieter Pypers:** Conceptualization, Data curation, Methodology, Investigation, Writing – review & editing, Funding acquisition, Project lead. **Johan Six:** Conceptualization, Data curation, Methodology, Investigation, Supervision, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

We thank the Bill & Melinda Gates Foundation (BMF) for funding the research as part of the African Cassava Agronomy Initiative (ACAI) project under the coordination of the International Institute of Tropical Agriculture (IITA), Nigeria, and in collaboration with the National Root Crops Research Institute (NRCRI), Nigeria, Federal University of Agriculture Abeokuta (FUNAAB), Nigeria, the Sasakawa African Association (SG200), Nigeria. We are also grateful to C. Okoli, N. Chijioko, J. Mbe, F. Nwanguma, I. I. Okonkwo, M. Asuo, O. Ekok, N. Ingya, and C. Ifenkwe for their assistance in the field.

References

- Adeniyani, O.N., Ayoola, O.T., 2007. Evaluation of four improved soybean varieties under different planting date in relayed cropping system with maize under soybean/maize/cassava intercrop. *Afr. J. Biotechnol.* 6 (19), 2220–2224. <https://doi.org/10.5897/AJB2007.000-2348>.
- Adeniyani, O.N., Aluko, O.A., Olanipekun, S.O., Olosoji, J.O., Aduramigba-Modupe, V.O., 2014. Growth and yield performance of cassava/maize intercrop under different plant population density of maize. *J. Agric. Sci.* 6 (8), 35–40. <https://doi.org/10.5539/jas.v6n8p35>.
- Adiele, J.G., Schut, A.G.T., van den Beuken, R.P.M., Ezui, K.S., Pypers, P., Ano, A.O., et al., 2020. Towards closing cassava yield gap in West Africa: agronomic efficiency and storage root yield responses to NPK fertilizers. *Field Crops Res.* 253 (November 2019), 107820. <https://doi.org/10.1016/j.fcr.2020.107820>.
- Alahira, J., 2013. Agro Ecological Zones in Nigeria. Retrieved from. <https://www.agriculturenigeria.com/manuals/research/introducing-agriculture-in-nigeria/agro-ecological-zone/>.
- Andersen, M.K., 2005. Competition and Complementarity in Annual Intercrops – The Role of Plant Available Nutrients. Thesis. The Royal Veterinary and Agricultural University, Copenhagen, Denmark, Department of Soil Science.

- Asiimwe, A., Tabu, I.M., Lemaga, B., Tumwegamire, S., Road, J.K., Towers, Z., Ababa, A., 2016. Effect of maize intercrop plant densities on yield and β -carotene contents of orange-fleshed sweetpotatoes (*Ipomoea batatas* L.). *Afr. Crop Sci. J.* 24 (1), 75–87.
- Ayodele, O.J., Omotoso, S.O., 2008. Nutrient management for maize production in soils of the savannah zone of south-western Nigeria. *Int. J. Soil Sci.* 3 (1), 20–27. <https://doi.org/10.3923/ijss.2008.20.27>.
- Ayoola, O.T., Makinde, E.A., 2007. Fertilizer treatment effects on performance of cassava under two planting patterns in a cassava-based cropping system in South West Nigeria. *Res. J. Agric. Biol. Sci.* 3 (1), 13–20.
- Bağ, K., Gaj, R., Budka, A., 2016. Accumulation of nitrogen, phosphorus and potassium in mature maize under variable rates of mineral fertilization. *Fragm. Agron* 33 (1), 7–19.
- Băşa, A.G., Ion, V., Dumbravă, M., Temocico, G., Epure, L.I., Ştefan, D., 2016. Grain yield and yield components at maize under different preceding crops and nitrogen fertilization conditions. *Agric. Agric. Sci. Procedia* 10, 104–111. <https://doi.org/10.1016/j.aaspro.2016.09.025>.
- Bates, D., Mächler, M., Bolker, B.M., Walker, S.C., 2015. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* 67 (1) <https://doi.org/10.18637/jss.v067.i01>.
- Cenpukdee, U., Fukai, S., 1992. Cassava/legume intercropping with contrasting cassava cultivars. 1. Competition between component crops under three intercropping conditions. *Field Crops Res.* 29 (2), 113–133. [https://doi.org/10.1016/0378-4290\(92\)00082-K](https://doi.org/10.1016/0378-4290(92)00082-K).
- Chambers, J., Freeny, A., Heiberger, R.M., et al., 1992. *Fit an Analysis of Variance Model. Statistical Model. S. Wedsworth and Brooks/Cole*, pp. 2–3.
- CHIRPS, 2020. Climate Hazards Group Infrared Precipitation with Station Data. Retrieved August 16, 2020, from <https://climateserv.servirglobal.net/>.
- Chukwu, L.I., 2019. Potential of vermesfluid for sustainable cassava production on a degraded ultisol of Southeastern Nigeria. *Univers. J. Agric. Res.* 7 (5), 189–195. <https://doi.org/10.13189/ujar.2019.070503>.
- CIMMYT, 1988. From Agronomic Data to Farmer Recommendations: An Economics Training Manual (1988). Retrieved from <https://repository.cimmyt.org/xmlui/bitstream/handle/10883/859/25152.pdf>.
- de Moura, E.G., Gehring, C., Braun, H., Junior, A.D.S.L.F., Reis, F., de O., Aguiar, A., das, C.F., 2016. Improving farming practices for sustainable soil use in the humid tropics and rainforest ecosystem health. *Sustainability (Switzerland)* 8 (9), 1–21. <https://doi.org/10.3390/su8090841>.
- Delaquis, E., de Haan, S., Wyckhuys, K.A.G., 2018. On-farm diversity offsets environmental pressures in tropical agro-ecosystems: a synthetic review for cassava-based systems. *Agric. Ecosyst. Environ.* 251 (2), 226–235. <https://doi.org/10.1016/j.agee.2017.09.037>.
- Duchene, O., Vian, J.F., Celette, F., 2017. Intercropping with legume for agroecological cropping systems: complementarity and facilitation processes and the importance of soil microorganisms. A review. *Agric. Ecosyst. Environ.* 240, 148–161. <https://doi.org/10.1016/j.agee.2017.02.019>.
- Egbe, O.M., Idoko, J.A., 2009. Agronomic assessment of some sweet potato varieties for intercropping with pigeon pea in Southern Guinea. *J. Agric. Biol. Sci.* 4 (4), 23–32. Retrieved from www.arpnjournals.com.
- Ekeleme, F., Akobundu, I.O., Isichei, A.O., Chikoye, D., Ekeleme, F., 2003. Cover crops reduce weed seedbanks in maize-cassava systems in Southwestern Nigeria. *Weed Sci. Soc. Am.* 51 (5), 774–780. Retrieved from <https://www.jstor.org/stable/pdf/4046560.pdf?refrefid=excelsior%3A8b2832ca9cc746a3167d0a54dad8843f>.
- Eke-okoro, O.N., Njoku, D.N., 2012. A review of cassava development in Nigeria from 1940-2010. *APRN J. Agric. Biol. Sci.* 7 (1), 59–65.
- Eze, S., 2010. *Dioscorea rotundata*. *Afr. J. Food Agric. Nutr. Dev.* 10 (6), 2755–2771.
- Ezui, K.S., Franke, A.C., Mando, A., Ahiabor, B.D.K., Tetteh, F.M., Sogbedji, J., et al., 2016. Fertiliser requirements for balanced nutrition of cassava across eight locations in West Africa. *Field Crops Res.* 185, 69–78. <https://doi.org/10.1016/j.fcr.2015.10.005>.
- Ezui, K.S., Franke, A.C., Leffelaar, P.A., Mando, A., Heerwaarden, J. Van, Sanabria, J., et al., 2017. Water and radiation use efficiencies explain the effect of potassium on the productivity of cassava. *Eur. J. Agron.* 83, 28–39. <https://doi.org/10.1016/j.eja.2016.11.005>.
- Fermont, A.M., Obiero, H., Van-Asten, J.J., Baguma, Y., Okwosa, E., 2007. Improved cassava varieties increase the risk of soil nutrient mining: an ex-ante analysis for western Kenya and Uganda. In: Bationo, A., Waswa, B., Kihara, J., Kimetu, J. (Eds.), *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*. Springer. Retrieved from https://link.springer.com/chapter/10.1007/978-1-4020-5760-1_48.
- Fermont, A.M., van Asten, P.J.A., Tittonell, P., van Wijk, M.T., Giller, K.E., 2009. Closing the cassava yield gap: an analysis from smallholder farms in East Africa. *Field Crops Res.* 112 (1), 24–36. <https://doi.org/10.1016/j.fcr.2009.01.009>.
- Fermont, Anneke M., Tittonell, P.A., Baguma, Y., Ntawuruhunga, P., Giller, K.E., 2010. Towards understanding factors that govern fertilizer response in cassava: lessons from East Africa. *Nutr. Cycl. Agroecosyst.* 86 (1), 133–151. <https://doi.org/10.1007/s10705-009-9278-3>.
- Gómez-Rubio, V., 2017. ggplot2 - elegant graphics for data analysis (2nd edition). *J. Stat. Softw.* 77, 2–5. <https://doi.org/10.18637/jss.v077.b02>. Book Review 2.
- Gou, F., van Iltersum, M.K., Wang, G., van der Putten, P.E.L., van der Werf, W., 2016. Yield and yield components of wheat and maize in wheat-maize intercropping in the Netherlands. *Eur. J. Agron.* 76, 17–27. <https://doi.org/10.1016/j.eja.2016.01.005>.
- Howeler, R.H., 2002. Cassava mineral nutrition and fertilization. *Cassava: Biology, Production and Utilization*, pp. 115–147. <https://doi.org/10.1079/9780851995243.0115>.
- Howeler, R.H., Cadavid, L.F., 1990. Short-and long-term fertility trials in Colombia to determine the nutrient requirements of cassava. *Fertil. Res.* 26 (1–3), 61–80. <https://doi.org/10.1007/BF01048744>.
- IITA, 2021. Maize. Retrieved January 12, 2021, from <https://www.iita.org/cropsnew/maize/>.
- ISRIC, 2020. World Soil Information. Retrieved from <https://soilgrids.org/>.
- Javaid, M., Ahmed, M., Rizwan, M., Ahmad, R., 2015. Intercropping to alleviate food scarcity in changing climate. *Technology Times*, pp. 10–12.
- Joseph, I., Agnes, A.G., Wanger, B., 2018. Cassava / maize intercrop yield response to different plant population densities in Makurdi and Lafia. *World J. Res. Rev.* 6 (3), 98–108.
- Kintché, K., Hauser, S., Mahungu, N.M., Ndonga, A., Lukombo, S., Nhamo, N., et al., 2017. Cassava yield loss in farmer fields was mainly caused by low soil fertility and suboptimal management practices in two provinces of the Democratic Republic of Congo. *Eur. J. Agron.* 89 (April), 107–123. <https://doi.org/10.1016/j.eja.2017.06.011>.
- Kolawole, G.O., 2013. Effects of leguminous plant residues and NPK fertilizer application on the performance of Yam (*Dioscorea rotundata* “c.v.” ewuru) in south-western Nigeria. *Arch. Agron. Soil Sci.* 59 (3), 423–434. <https://doi.org/10.1080/03650340.2011.638289>.
- Kreye, C., Hauser, S., Pypers, P., Vanlauwe, B., 2020. Intensification options of small holders' cassava production in South-west Nigeria. *Agron. J.* (August), 5312–5324. <https://doi.org/10.1002/agj2.20419>.
- Li, L., Jianhao, S., Fusuo, Z., Xiaolin, L., Sicun, Y., Zdenko, R., 2001. Wheat/maize or wheat/soybean strip intercropping I. Yield advantage and interspecific interaction on nutrients. *Field Crops Res.* 71 (2), 123–137. [https://doi.org/10.1016/S0378-4290\(01\)00156-3](https://doi.org/10.1016/S0378-4290(01)00156-3).
- Makurira, H., 2010. Rainfed agriculture in Sub-Saharan Africa. *Water Product. Rainfed Agric.* 181 (November 1947), 9–21. <https://doi.org/10.1201/b10823-3>.
- Meng, Q., Hou, P., Wu, L., Chen, X., Cui, Z., Zhang, F., 2013. Understanding production potentials and yield gaps in intensive maize production in China. *Field Crops Res.* 143, 91–97. <https://doi.org/10.1016/j.fcr.2012.09.023>.
- Midmore, D.J., 1993. Agronomic modification of resource use and intercrop productivity. *Field Crops Res.* 34, 357–380. Retrieved from <https://www.science-direct.com/science/article/pii/S0378429093901224>.
- Munyahali, W., Pieter, P., Swennen, R., Walangululu, J., Vanlauwe, B., 2017. Responses of cassava growth and yield to leaf harvesting frequency and NPK fertilizer in South Kivu, Democratic Republic of Congo. *Field Crops Res.* 214 (April), 194–201. <https://doi.org/10.1016/j.fcr.2017.09.018>.
- Muoneke, C.O., 2007. Effect of maize planting density on the performance of maize/soybean intercropping system in a guinea savannah agroecosystem. *Afr. J. Agric. Res.* 2 (12), 667–677.
- Muoneke, C.O., Asiegbu, J.E., 1997. Effect of okra planting density and spatial arrangement in intercrop with maize on the growth and yield of the component species. *J. Agron. Crop. Sci.* 179 (4), 201–207. <https://doi.org/10.1111/j.1439-037X.1997.tb00518.x>.
- NAAS, 2009. Crop Response and Nutrient Ratio (No. 42). Retrieved from https://webcache.googleusercontent.com/search?q=cache:Fq1pJPvaVLQJ:https://www.researchgate.net/file/PostFileLoader.html%3Fid%3D58070fb6ed99e1e005124bd2%26a_ssetKey%3DAS%253A418786042761216%25401476857781901+%&cd=16&hl=en&ct=clnk&gl=ch.
- Njoku, D.N., Muoneke, C.O., 2008. Effects of cowpea planting density on growth, yield and productivity of component crops in cowpea/cassava intercropping system. *J. Trop. Agri. Food Environ. Extens.* 7, 106–113.
- Ntawuruhunga, P., Ssemakula, G., Ojulong, H., Bua, A., Ragama, B., Kanobe, C., Whyte, J., 2006. Evaluation of Advanced Cassava Genotypes in Uganda. Retrieved from African Crop Science Society. <http://www.bioline.org.br/pdf?cs06002>.
- Obigbesan, G.O., Fayemi, A.A.A., 1976. Investigations on Nigerian root and tuber crops. *J. Agric. Sci.* 1976 (86), 401–406. Retrieved from <https://www.cambridge.org/core/journals/journal-of-agricultural-science/article/investigations-on-nigerian-root-and-tuber-crops-effect-of-potassium-on-starch-yields-hcn-content-and-nutrient-uptake-of-cassava-cultivars-manihot-esculenta/57597B7845CC4E40D4F>.
- Olasantan, F.O., Lucas, E.O., Ezumah, H.C., 1994. Effects of intercropping and fertilizer application on weed control and performance of cassava and maize. *Field Crops Res.* 39 (2–3), 63–69. [https://doi.org/10.1016/0378-4290\(94\)90009-4](https://doi.org/10.1016/0378-4290(94)90009-4).
- Olasantan, F.O., Ezumah, H.C., Lucas, E.O., 1996. Effects of intercropping with maize on the micro-environment, growth and yield of cassava. *Agric. Ecosyst. Environ.* 57 (2), 149–158. [https://doi.org/10.1016/0167-8809\(96\)01019-5](https://doi.org/10.1016/0167-8809(96)01019-5).
- Olasantan, F.O., Ezumah, H.C., Lucas, E.O., 1997. Response of Cassava and Maize to Fertilizer Application, and a Comparison of the Factors Affecting their Growth During Intercropping. (1990).
- Onasanya, O.O., Hauser, S., Necpalova, M., Salako, F.K., Kreye, C., Tariku, M., et al., 2020. On-farm assessment of cassava root yield response to tillage, plant density, weed control and fertilizer application in southwestern Nigeria. *Field Crops Res.* 262 <https://doi.org/10.1016/j.fcr.2020.108038>.
- Plesis, du J., Bruwer, D., de V., Mashao, J., Pretorius, A., Prinsloo, T., 2003. Maize Production. Retrieved from Agriculture Republic of South Africa, pp. 1–38. www.nda.agric.za/publications.
- Pypers, P., Bimponda, W., Lodi-Lama, J.P., Lele, B., Mulumba, R., Kachaka, C., et al., 2012. Combining mineral fertilizer and green manure for increased, profitable cassava production. *Agron. J.* 104 (1), 178–187. <https://doi.org/10.2134/agronj2011.0219>.
- Qiu, S., Xie, J., Zhao, S., Xu, X., Hou, Y., Wang, X., et al., 2014. Long-term effects of potassium fertilization on yield, efficiency, and soil fertility status in a rain-fed maize system in northeast China. *Field Crops Res.* 163, 1–9. <https://doi.org/10.1016/j.fcr.2014.04.016>.
- R Core Team, 2020. The R Project for Statistical Computing (3.4.4)[software]. Retrieved from <https://www.r-project.org/>.

- Rahmani, A., 2016. Effect of planting date and plant densities on yield and yield components of sweet corn (*Zea mays* L. var *saccharata*). *Am. J. Exp. Agric.* 10 (2), 1–9. <https://doi.org/10.9734/ajea/2016/19592>.
- Rusinamhodzi, L., Corbeels, M., Nyamangara, J., Giller, K.E., 2012. Maize-grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. *Field Crops Res.* 136 (August), 12–22. <https://doi.org/10.1016/j.fcr.2012.07.014>.
- Saïdou, A., Janssen, B.H., Temminghoff, E.J.M., 2003. Effects of soil properties, mulch and NPK fertilizer on maize yields and nutrient budgets on ferralitic soils in southern Benin. *Agric. Ecosyst. Environ.* 100 (2–3), 265–273. [https://doi.org/10.1016/S0167-8809\(03\)00184-1](https://doi.org/10.1016/S0167-8809(03)00184-1).
- Saïdou, A., Balogoun, I., Ahoton, E.L., Igué, A.M., Youl, S., Ezui, G., Mando, A., 2018. Fertilizer recommendations for maize production in the South Sudan and Sudano-Guinean zones of Benin. *Nutr. Cycl. Agroecosystems* 110 (3), 361–373. <https://doi.org/10.1007/s10705-017-9902-6>.
- Salako, F.K., 2003. Soil physical conditions in Nigerian Savannas and biomass production. Lecture given at the College on Soil ..., (March), 14. Retrieved from <http://tropical-dry-forest-biome.doculib.org/download/soil-physical-conditions-in-nigerian-savannas-and-biomass-production.pdf>.
- Salau, A.W., Olaniran, F.O., Bodunde, J.G., 2011. Effect of intercropping pumpkin with cassava on soil micro-environment, weed control, crop growth and yields. *J. Agric. Sci. Environ.* 11 (1), 114–127.
- Senkoro, C.J., Tetteh, F.M., Kibunja, C.N., Ndungu-Magiroi, K.W., Quansah, G.W., Marandu, A.E., et al., 2018. Cassava yield and economic response to fertilizer in Tanzania, Kenya and Ghana. *Agron. J.* 110 (4), 1600–1606. <https://doi.org/10.2134/agronj2018.01.0019>.
- Silva, D.V., Ferreira, E.A., Oliveira, M.C., Pereira, G.A.M., Braga, R.R., dos Santos, J.B., et al., 2016. Productivity of cassava and other crops in an intercropping system. *Cienc. E Invest. Agrar.* 43 (1), 15. <https://doi.org/10.4067/s0718-16202016000100015>.
- Sogbedji, M.J., Lakpo, K.A., Kodjovi, S.D., Ruth, A., Mihikouwe, M., 2015. Sustaining improved cassava production on West African ferralsols through appropriate varieties and optimal potassium fertilization schemes. *J. Plant Sci. (Science Publishing Group)* 3 (3), 117. <https://doi.org/10.11648/j.jps.20150303.12>.
- Sommer, R., Bossio, D., Desta, L., Dimes, J., Kihara, J., Koala, S., et al., 2013. Profitable and Sustainable Nutrient Management Systems for East and Southern African Smallholder Farming Systems – Challenges and Opportunities, (May), 91. <https://doi.org/10.13140/RG.2.1.2498.2642>.
- Testa, G., Reyneri, A., Blandino, M., 2016. Maize grain yield enhancement through high plant density cultivation with different inter-row and intra-row spacings. *Eur. J. Agron.* 72, 28–37. <https://doi.org/10.1016/j.eja.2015.09.006>.
- Thandar, N., 2014. Improving Agronomic Efficiency in Cassava-Based Farming Systems in the Democratic Republic of Congo Using Organic and Inorganic Inputs. Retrieved from. Kenyatta University. [https://ir-library.ku.ac.ke/bitstream/handle/123456789/11159/Improving agronomic efficiency in cassava-based farming systems in the democratic republic of Congo using organic and inorganic inputs.pdf;sequence=1](https://ir-library.ku.ac.ke/bitstream/handle/123456789/11159/Improving%20agronomic%20efficiency%20in%20cassava-based%20farming%20systems%20in%20the%20democratic%20republic%20of%20congo%20using%20organic%20and%20inorganic%20inputs.pdf;sequence=1).
- Thierfelder, 2013. Integration of conservation agriculture in smallholder farming systems of southern Africa: identification of key entry points. *Int. J. Agric. Sustain.* 11 (4), 317–330. <https://doi.org/10.1080/14735903.2013.764222>.
- Yadav, R.K., Verma, A., Yadav, S.L., Sumariya, H.K., 2017. Dry matter partitioning at harvest and yield of maize (*Zea mays* L.) as influenced by integration of various nutrients. *Int. J. Curr. Microbiol. Appl. Sci.* 6 (6), 2942–2945. <https://doi.org/10.20546/ijcm.2017.606.349>.
- Yousaf, M., Li, J., Lu, J., Ren, T., Cong, R., Fahad, S., Li, X., 2017. Effects of fertilization on crop production and nutrient-supplying capacity under rice-oilseed rape rotation system. *Sci. Rep.* 7 (1), 1–9. <https://doi.org/10.1038/s41598-017-01412-0>.